Coding, Modulation, and Cross Polarization Techniques at Data Rates Greater Than 300 Mb/s for X-Band

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Baud Rate Limitations Imposed By DSN Emission Requirements

- Previously it was shown that 200 Mb/s is a reasonable number for the upper limit on baud rate at X-band due to the DSN.
- Further it was shown that by offsetting the center frequency to 8185 MHz and Nyquist filtering that 200 Mb/s baud rate was achievable.
- This implies that with QPSK or OQPSK that 400 Mb/s transmission rate is feasible and with 8PSK a 600 Mb/s transmission rate is feasible.

Error Correction Coding

- Since the transmit rate for a coded signal has to be greater than the information rate it would seem that error correction coding would reduce the maximum transmission rate of information at X-band.
- It shall be shown, however, that coding will make cross polarization transmission feasible.

Coding At High Data Rates

- Convolutional encoding / Virterbi decoding
  - Fastest commercial chip 45 Mb/s info rate, 90 Mb/s TX rate.
  - Fastest FPGA core 155 Mb/s info rate, 310 Mb/s TX rate.
  - 5.1 to 5.2 dB coding gain at rate 1/2.
- Turbo coding
  - Hot research area.
  - Turbo code standard for UMTS
  - Commercial chip 155 Mb/s information rate, $r > 0.9$.
- Self - orthogonal convolutional code using threshold decoding with syndrome feedback.
  - $r = 7/8$, $J = 6$, $N_a = 1176$
  - Structure allows implementation at high data rates even up to Gb/s rates.
  - At low error rates the coding gain is as good or better than $r = 7/8$ punctured Virterbi.
  - Coder used in the 280 Mb/s information rate 320 Mb/s transmit rate Nyquist OQPSK system discussed in the previous paper “Filtering to Meet DSN Requirements at High Data Rates,” by Dr. James S. Gray.

System On Chip (SOC) Dilemma

- Have ability to put many tens of millions of transistors on an IC at present time
- Requires very high volumes to justify cost of development (eg. Microprocessors, cell phones, direct broadcast of television, etc.)
- Example development cost: $400 million for GSM / WCDMA cell phone
- Functional blocks are only part of a complex IC used in a specific application
- Thus hard to get ubiquitous functional blocks for moderate or low volume usage
- Partial solution is FPGAs and DSP ICs

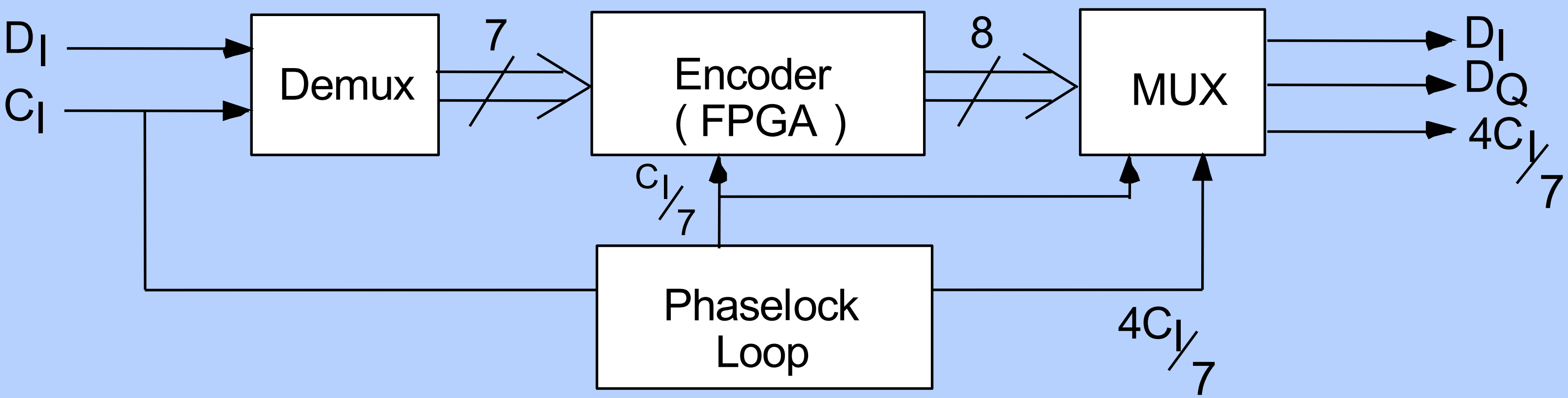

Figure 1. Self-orthogonal Convolutional Encoder Block Diagram

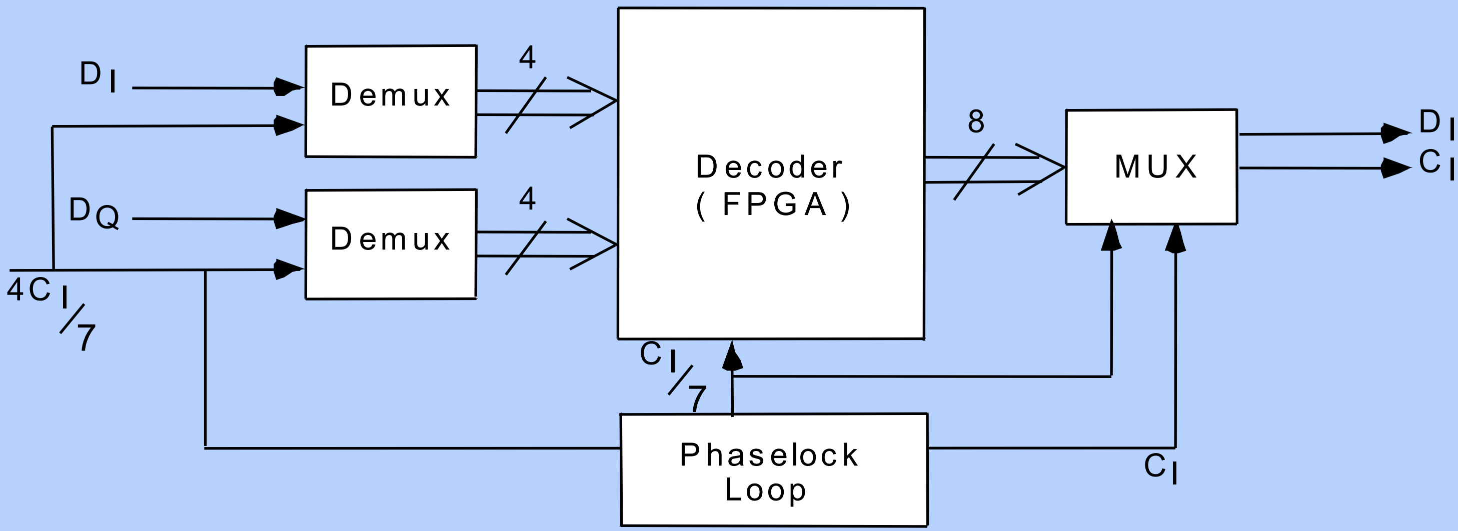

Figure 2. FEC Decoder Block Diagram

- 3.55 dB coding gain at 10^{-8}
- 3.70 dB coding gain at 10^{-9}

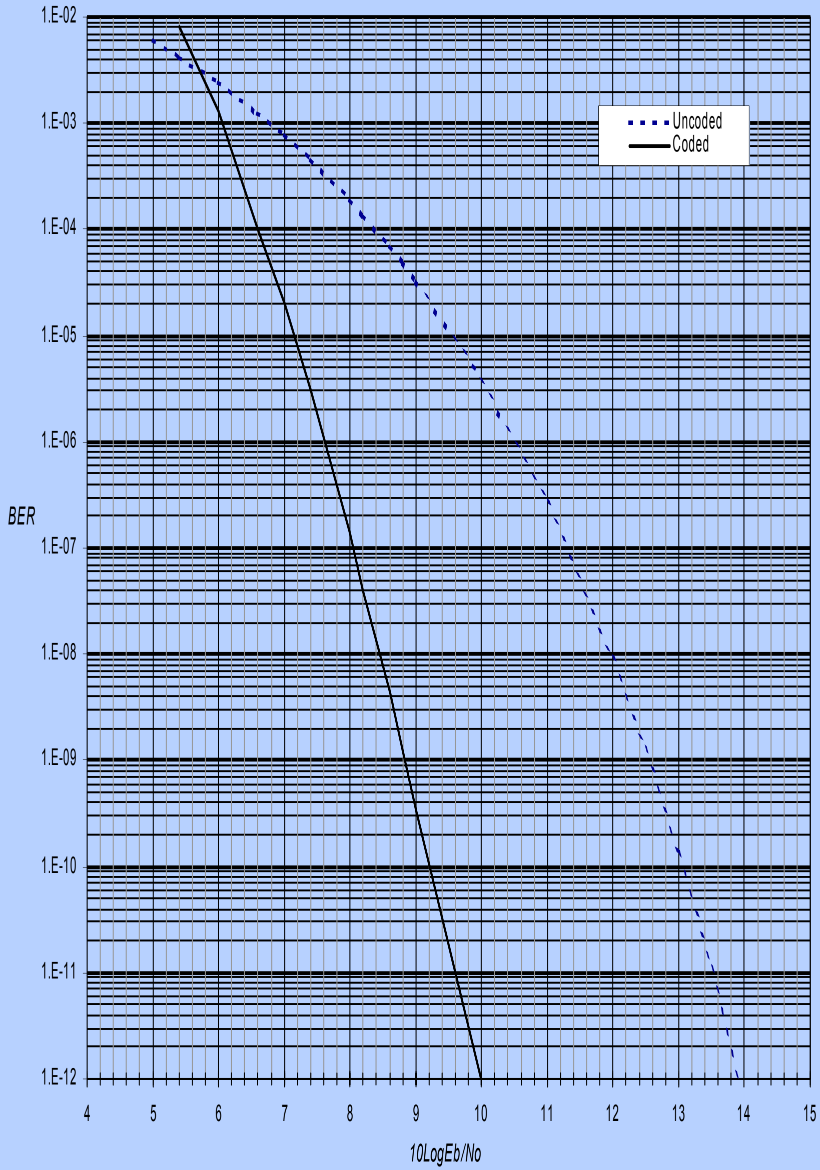

Figure 3. Theoretical Coded vs Uncoded BER Performance

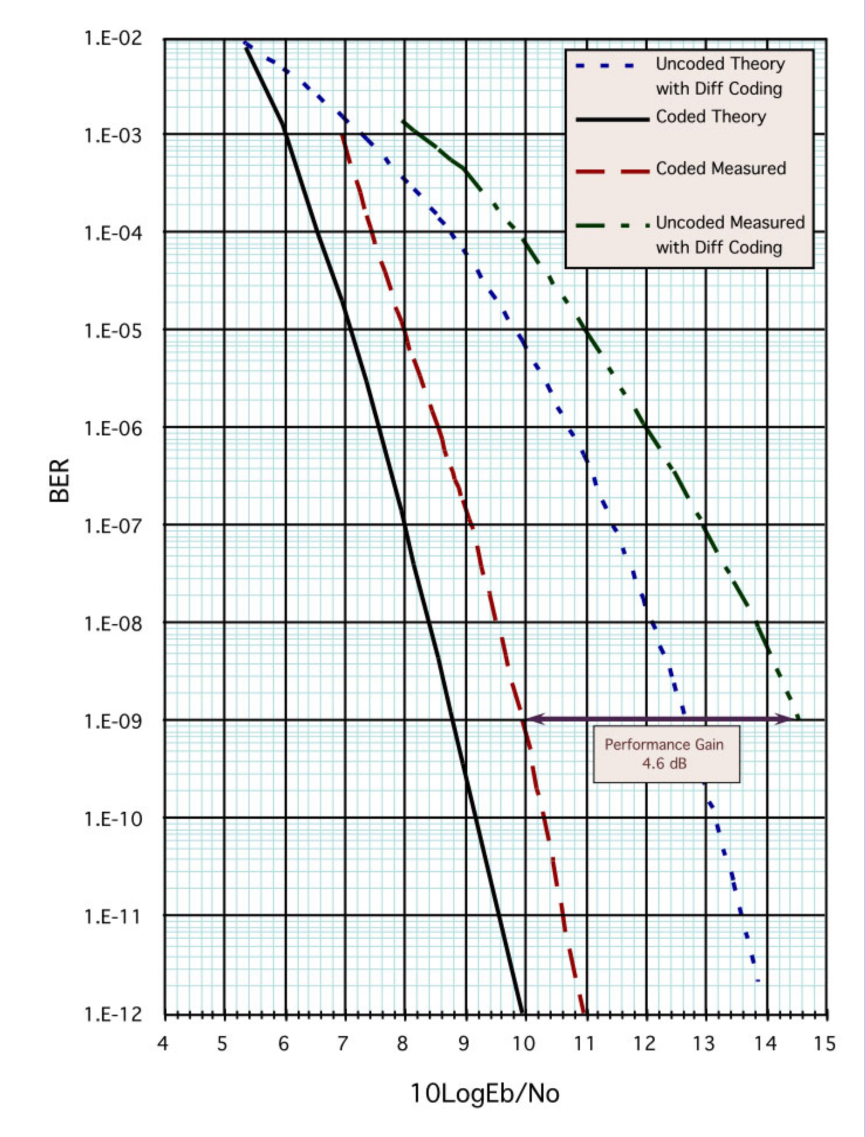

Figure 4. Measured Coding Gain, 280 Mb/s Information Rate, 320 Mb/s Transmission Rate Nyquist OQPSK System

Forward Error Correction Coding Makes A Cross Polarization High Data Rate Nyquist OQPSK System Extremely Feasible

- The use of r = 7/8 forward error correction coding results in measured performance at a 1E-9 error rate at an Eb/No that is 4.6dB less than that required for uncoded operation.
- The total performance gain is comprised of coding gain, elimination of differential coding, and a shift in the modem operating point.
- While significant performance gain is achieved, the use of a high rate r = 7/8 code only spreads the spectrum by a factor of 8/7.
- Operation at lower 10log Eb/No levels minimizes the effect of a cross polarization leakage signal.
- We have seen that the maximum X-band OQPSK transmission rate is 400 Mb/s. This implies a 350 Mb/s information rate.
- Thus transmitting cross polarized signals allows one to achieve a total information rate of 700 Mb/s and transmit rate of 800 Mb/s.

Relative Cross Polarized Signal Level	Additional Degradation in dB at 10e-9 BER
60 dB	0
30 dB	0
25 dB	0.18
20 dB	0.58
15 dB	1.68

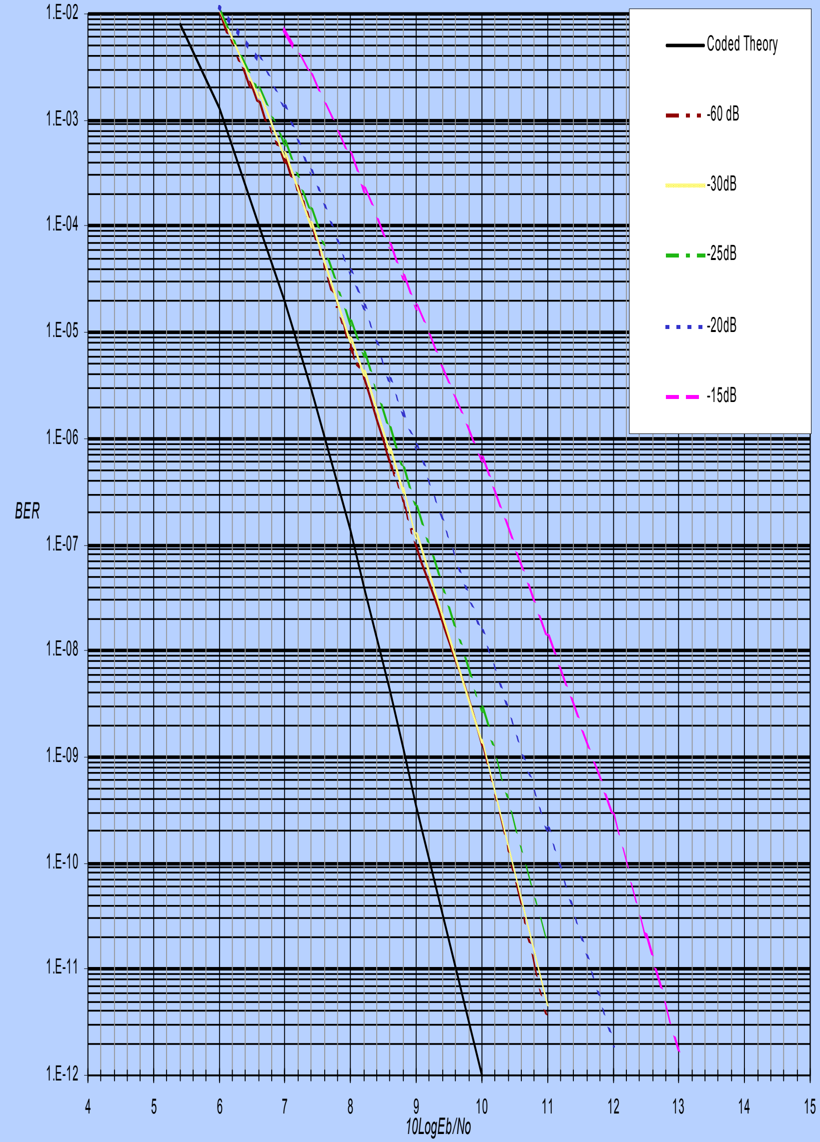

Figure 5. Measured Effect Of Cross Polarization Leakage Signal On Coded Nyquist OQPSK System

Modulation Techniques For Increasing Bit Rate at X-Band

- Satellite communications has historically been power limited and now bandwidth limited.
- Because of the power limitation lower order modulation types such as BPSK, QPSK, AQPSK, OQPSK, and UQPSK which use antipodal signaling have been used.
- The pressing need for higher data rates at X-band is forcing consideration of 8PSK even though greater Eb/No is required for a given BER.
- For example at a 10^{-5} error rate ~ 3.4 dB more power is required than QPSK / BPSK and due to the sensitivity of higher order modulation the equipment may well perform an additional 1 dB from theory. Thus the net power required might be 4.4 dB higher for 8PSK vs. QPSK at 10^{-5}.

~ 3.4 dB difference

at 10^{-5} BER

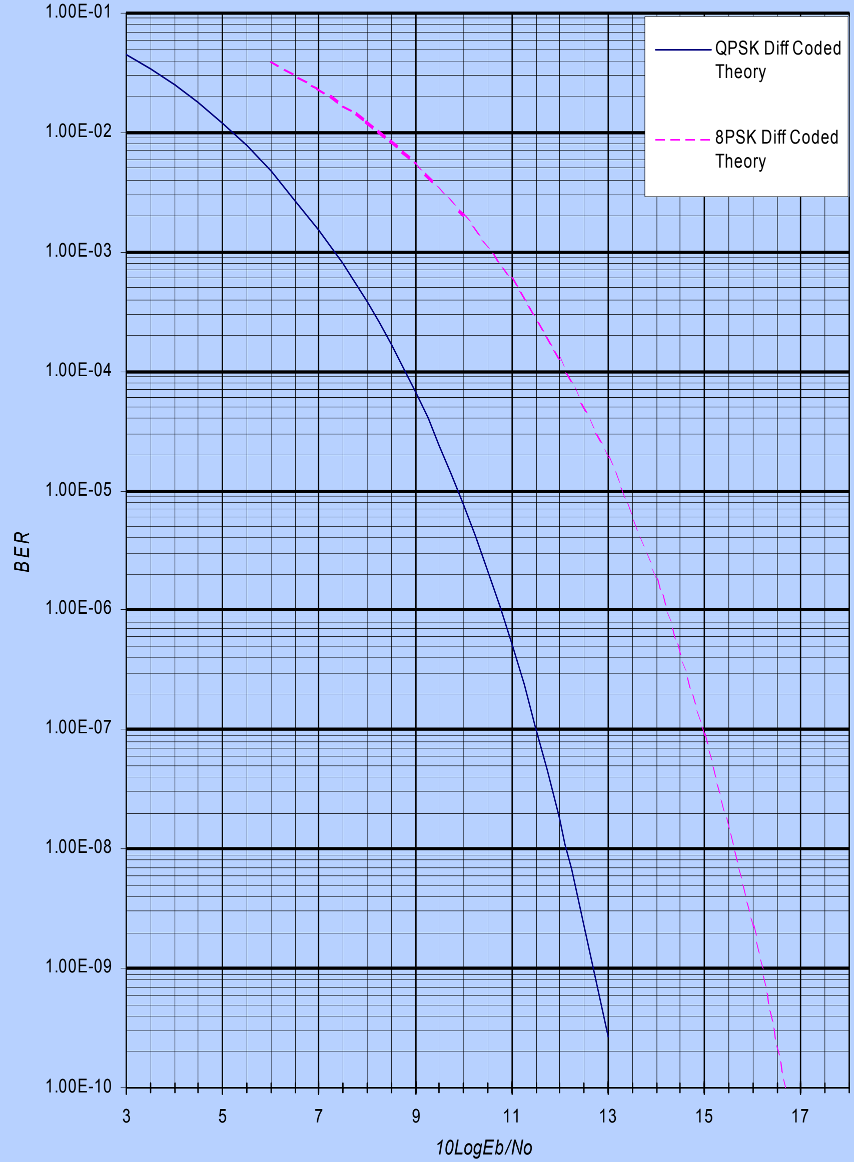

Figure 6. BER For Diff Coded QPSK and Diff Coded 8PSK

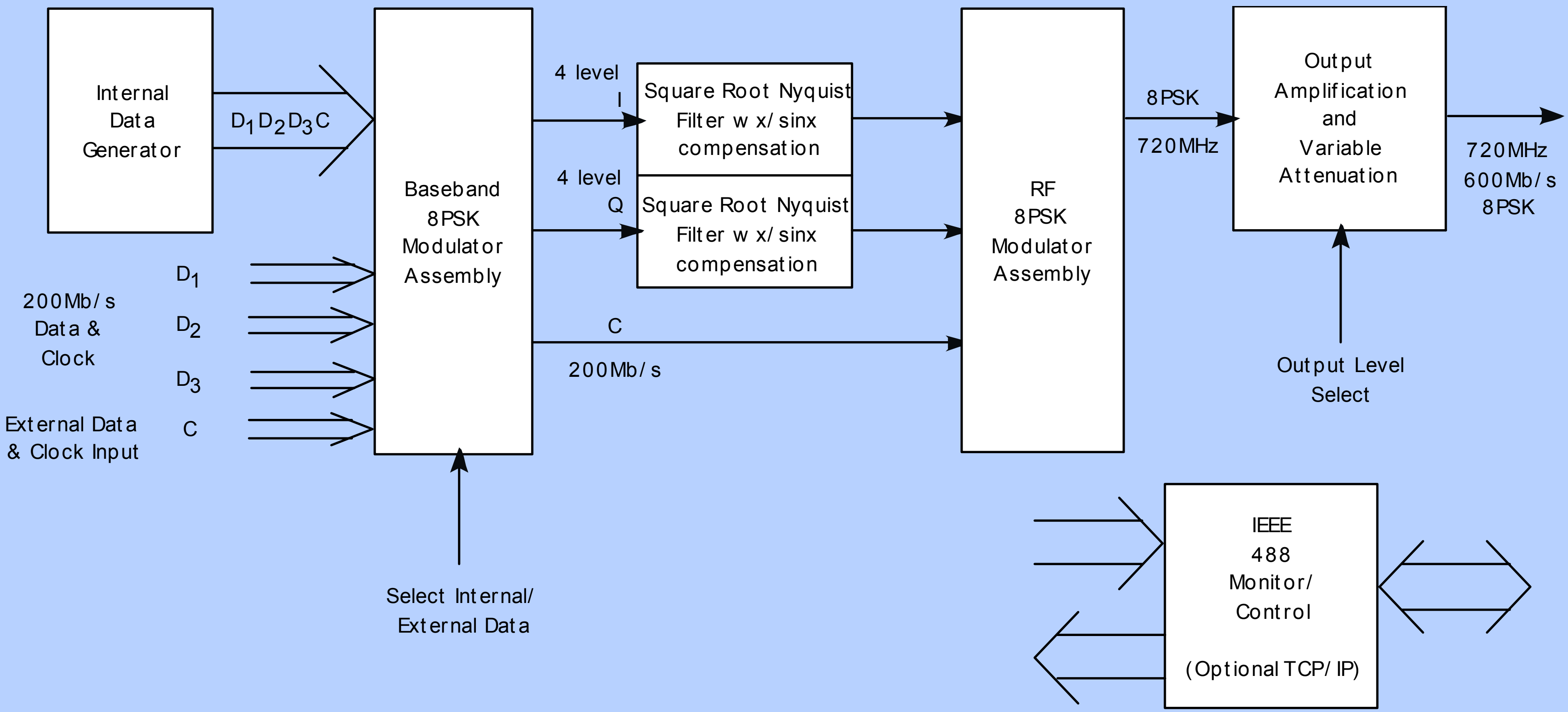

Figure 7. 600 Mb/s Nyquist 8PSK Modulator Block Diagram

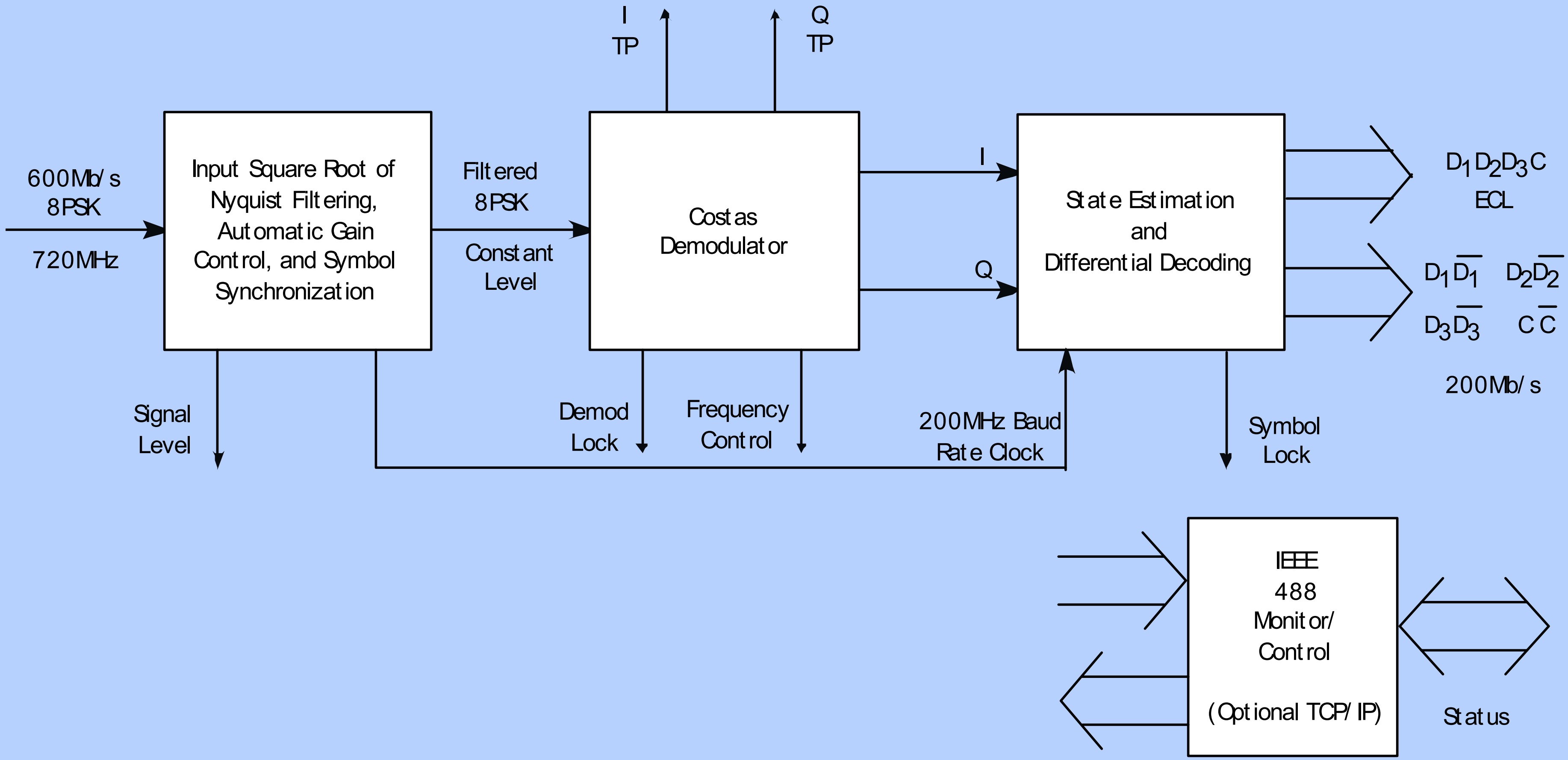

Figure 8. 600 Mb/s Nyquist 8PSK Demodulator Block Diagram

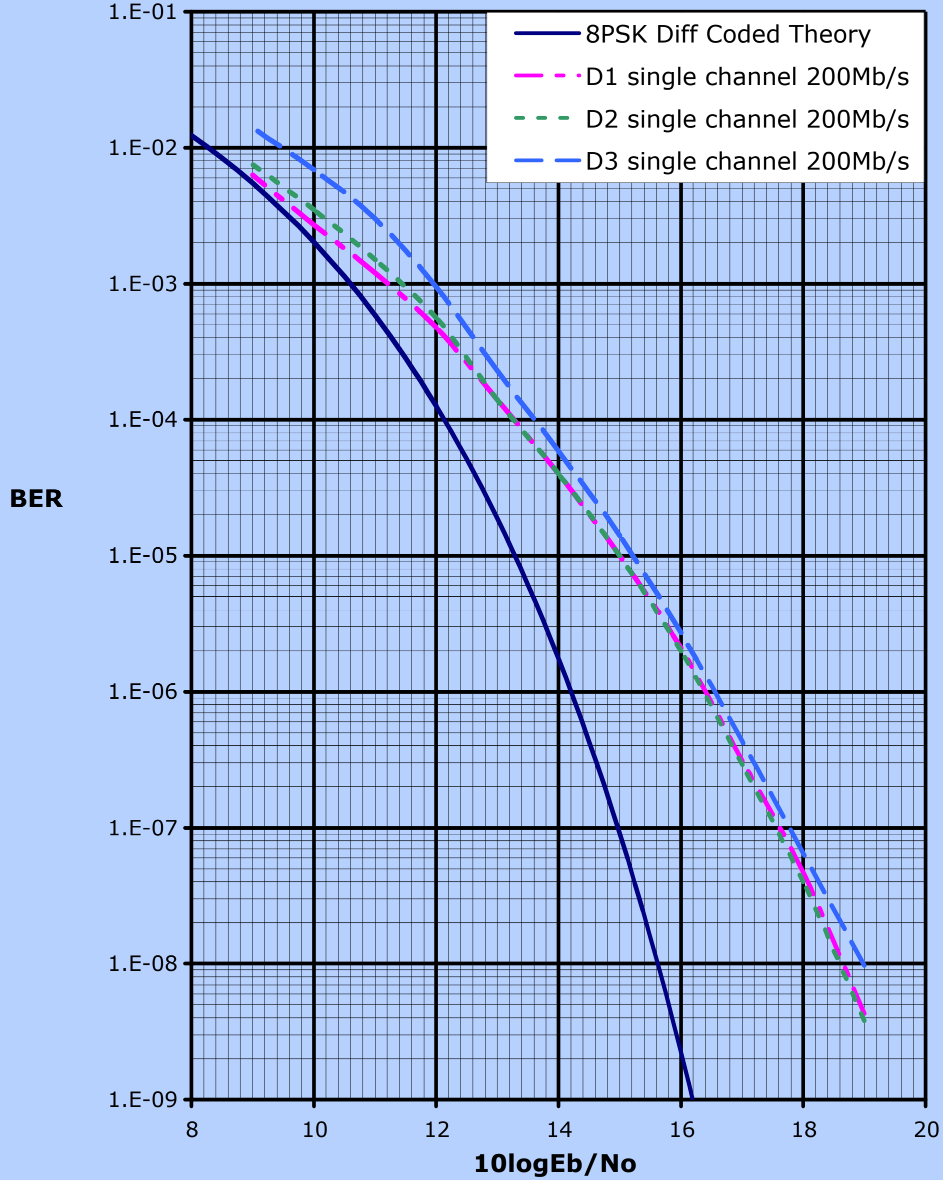

Figure 9. Measured Performance Of 600 Mb/s Nyquist 8PSK Modulator and Demodulator

~ 1.8 dB delta from theory at 10^{-5} BER

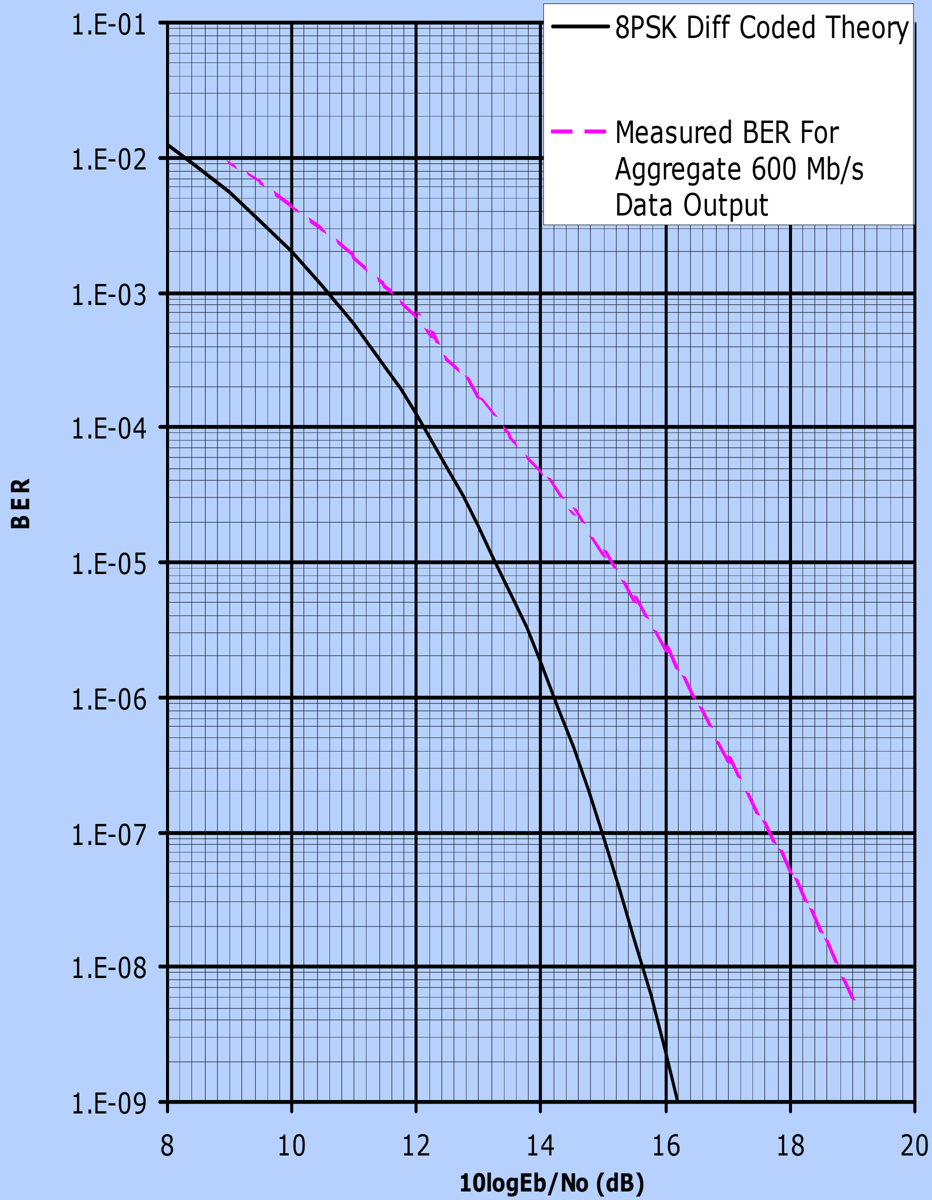

Figure 10. Measured Performance Of The Aggregate Output Of The 600 Mb/s Nyquist 8PSK Modulator and Demodulator

Modulation Conclusions For High Data Rates At X-Band

- From a modulation standpoint, Nyquist 400 Mb/s OQPSK operation at X-band is completely feasible.
- Operational hardware at 400 Mb/s is a very slight extension of existing high data rate hardware.
- Likewise from a modulation standpoint, Nyquist 600 Mb/s 8PSK operation at X-band is completely feasible.
- Measured performance for Nyquist 600 Mb/s equipment is within the specified operational tolerance.
- Thus both 400 Mb/s OQSK and 600 Mb/s 8PSK operational systems at X-band are achievable.

For a cross polarized 600 Mb/s Nyquist 8PSK system allowing an aggregate 1200 Mb/s transmission rate what is the effect of the cross polarization leakage signal?

- The degradation will be worse for higher order modulation such as 8PSK than it would be for OQPSK.
- The effect on uncoded operation is worse than that for a coded operation.

Relative Cross-Polarized Signal Level	Additional Degradation in dB at 10e-5 BER
60 dB	0
25 dB	1.1
20 dB	3

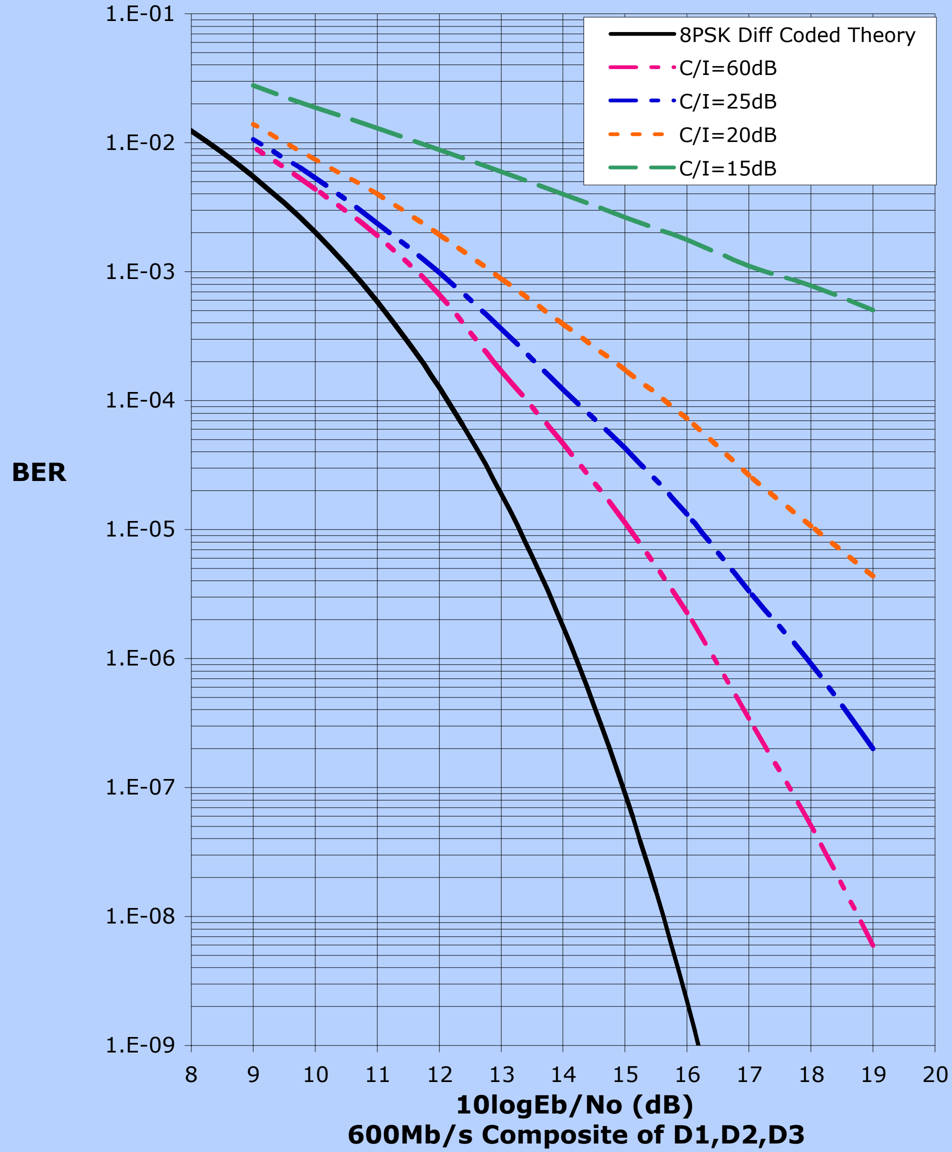

Figure 11. Performance of 600Mb/s 8PSK Hardware with Cross-Polarized Leakage of similar signal

Conclusions for Cross Polarized Uncoded 1200 Mb/s Nyquist 8PSK System

- If polarization leakage can be controlled, such that leakage of the other polarization signal is greater than 20 dB below the desired signal, then a cross polarized uncoded system is feasible.
- Adding R=7/8 error correction coding would greatly reduce the effect of the cross polarized leakage signal on the desired coded signal.
- With error correction coding one can achieve a 1050 Mb/s information rate system at X-band with a transmission rate of 1200 Mb/s.

Considerations for Error Correction Coding Equipment Topology for 8PSK

- Data input for each polarization will be three 175 Mb/s data streams instead of one 525 Mb/s serial data stream.
- Since there is no common denominator between 3, 7, and 8 one should encode each of the three data streams separately.
- One can use a common timing loop for all three encoders
- Therefore, Modulo 8 differential encoding of the data should occur before error correction coding.
- This topology will determine the FEC decoder and differential decoder topology.
- These topologies are presented in the following two figures.

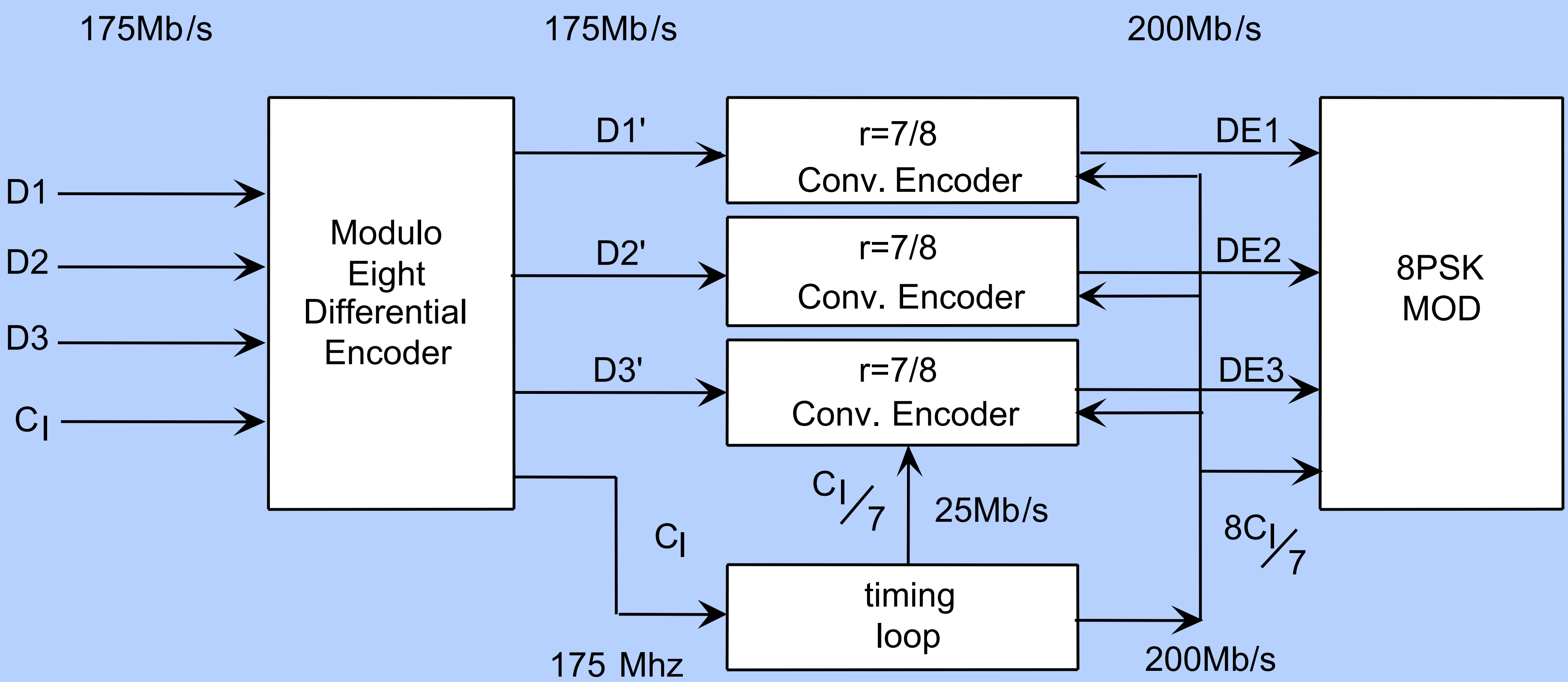

Figure 12. Proposed Topology for Differential coding and Convolutional Coding for Spacecraft

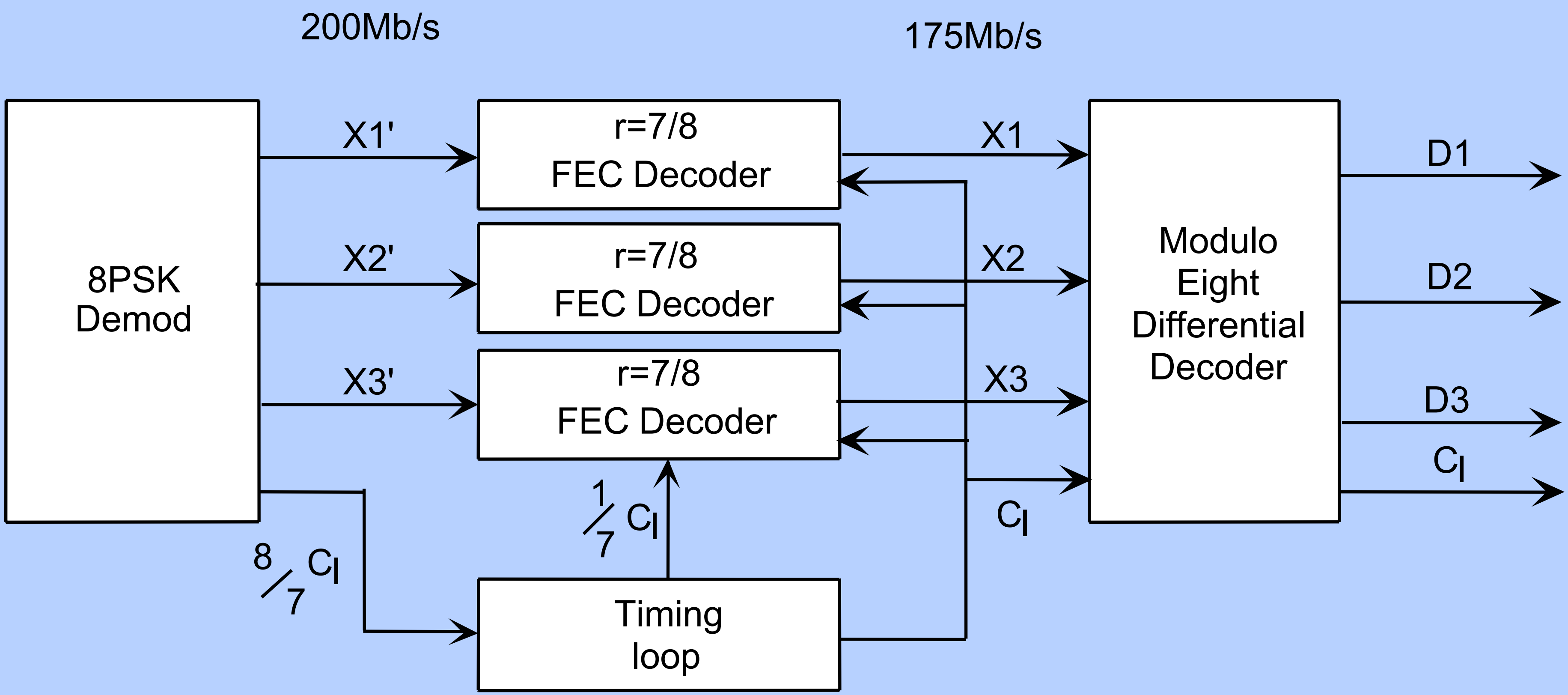

Figure 13. Proposed Topology for Differential Decoding and Convolutional Decoding Spacecraft

Conclusions on Adding Error Correction Coding to the Nyquist 8PSK System

- Structure of the encoder and decoder allows easy implementation at this data rate with existing FPGAs and ECL front and back end logic.
- Performance improvement will result from coding gain, shifting of the demodulator’s operating point, and the reduced effect of the cross polarized leakage signal at a given error rate.
- It is strongly recommended that cross polarized high data rate 8PSK system include error correction coding.

X-Band vs. Ka-Band

- At Ka-Band 1.5 GHz of bandwidth is available and there are no restrictions due to the DSN, thus filtering is much simpler and high data rates are easily achievable.
- For this reason, operation at Ka-Band should use a form of QPSK modulation vs a higher order modulation such as 8PSK.
- Spacecraft components and ground equipment at Ka-Band are much more expensive than equipment at X-Band at the current time. Equipment choices are also much more limited.
- The effect of atmospheric perturbations is much more severe at Ka-Band.

Overall Conclusions

- To maximize the data rate at X-Band with the restrictions imposed by the DSN one should use the following techniques
  - Optimized transmitter topology
  - Offset center frequency
  - Nyquist filtering with X/Sin X correction
  - Modulation type
  - Error correction coding
  - Transmittal of two coded signals on cross polarized carriers

Overall Conclusions Cont.

- The use of these techniques in conjunction with the hardware developments presented allow low risk implementation of the following X-Band high data rate systems
  - Nyquist uncoded 400 Mb/s OQPSK system
  - Coded 700 Mb/s information rate, 800 Mb/s transmission rate cross polarized Nyquist OQPSK system.
  - Nyquist uncoded 600 Mb/s 8PSK system
  - Coded 1050 Mb/s information rate, 1200 Mb/s transmission rate cross polarized Nyquist 8PSK system